

PERSPECTIVES FOR MUON COLLIDERS AND NEUTRINO FACTORIES

M. Bonesini

*Sezione INFN Milano Bicocca, Dipartimento di Fisica G. Occhialini,
Università di Milano Bicocca, Milano, Italy.*

Abstract

High brilliance muon beams are needed for future facilities such as a Neutrino Factory, an Higgs-factory or a multi-TeV Muon Collider. The *R&D* path involves many aspects, of which cooling of the incoming muon beams is essential.

1 Introduction

Since the 1960's, Muon Colliders (MC) [1] and Neutrino Factories (NF) [2], based on high brilliance muon beams, have been proposed. Their design has been optimized in references [3], [4], [5],[6] and [7]. While a MC addresses the high-energy frontier: looking at precise Higgs physics [8] and beyond, a NF will provide the ultimate tool for neutrino oscillation studies, looking at CP-violation. The current design of a NF or a MC front-end is similar, up to the beginning of the cooling section, as can be seen from the layouts reported in figure 1.

MC's may be developed with c.m.s energy up to many TeV and, due to the large μ mass as compared to the electron one, may easily fit in the footprint of existing HEP laboratories ¹

s-channel scalar Higgs production is greatly enhanced in a $\mu^+\mu^-$ collider (as respect to e^+e^-) as the coupling is proportional to the lepton mass. Precision measurements in the Higgs sector are thus feasible: at $m_{H^0} \sim 126 \text{ GeV}/c^2$ only a $\mu^+\mu^-$ collider may directly measure the H^0 lineshape. With an integrated luminosity of 0.5 fb^{-1} , the H^0 mass may be determined, in the Standard Model case, with a precision of $0.1 \text{ MeV}/c^2$ and its width $\Gamma_{H^0}(\sim 4 \text{ MeV}/c^2)$ with a precision of $0.5 \text{ MeV}/c^2$.

¹A $\sqrt{s} = 3 \text{ TeV}$ Muon Collider ($\mu^+\mu^-$ Higgs Factory) has a ring circumference of $\sim 6.3(\sim 0.3) \text{ km}$, to be compared to the $\sim 26 \text{ km}$ of the LHC tunnel.

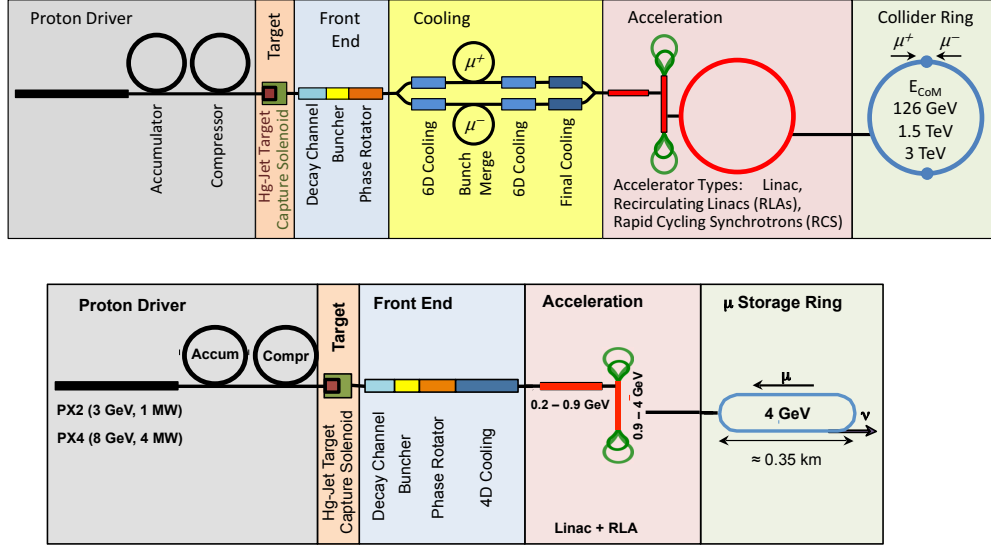


Figure 1: Schematic layout of a MC (top) and a NF (bottom).

Through the processes $\mu^- \mapsto e^- \nu_\mu \bar{\nu}_e$ and $\mu^+ \mapsto e^+ \bar{\nu}_\mu \nu_e$, neutrino beams with a flux known at better than 1% and well-known composition (50% ν_μ or $\bar{\nu}_\mu$, 50% $\bar{\nu}_e$ or ν_e) may be produced in a NF [9]. The “golden channel” linked to $\nu_e \mapsto \nu_\mu$ (or $\bar{\nu}_e \mapsto \bar{\nu}_\mu$) oscillations, manifests itself by wrong sign muons, as respect to initial beam charge, suggesting the use of large magnetized far detectors. After the experimental discovery of a large θ_{13} value, $\sim 5\%$, the design of the NF has been revised to improve precision in the study of sub-leading effects in neutrino oscillations and provide better capabilities for the measurement of the phase δ , if leptonic CP-violation occurs [7].

2 R&D towards a muon collider and a neutrino factory

Many R&D issues are relevant for the development of a NF or a MC, such as the availability of a suitable proton driver or a high-power target, but the most critical one is still the muon cooling. Muons are produced as tertiary particles in the process chain $pA \mapsto \pi X, \pi \mapsto \mu \nu$ and thus occupy a large longitudinal and transverse phase space. Conventional accelerator technologies require input beams with small phase space. To alleviate this problem one may use either new large aperture accelerators, such as “fixed field alternating-gradient” (FFAG)

machines [10] or try to reduce (“cool”) the incoming muon beam phase space. While for a NF the required cooling factor is small: around 2.4 for the 75 m cooling section in the IDS-NF design [5], [7], for a MC a longitudinal emittance reduction ~ 14 and a transverse emittance reduction ~ 400 in both transverse coordinates are needed, requiring a total cooling factor $\sim 2 \times 10^6$.

2.1 Ionization cooling and the MICE experiment at RAL

Conventional beam cooling methods do not work on the short timescale of the muon lifetime ($\tau \sim 2.2\mu\text{s}$). The only effective way is the so-called “ionization cooling” that is accomplished by passing muons through a low- Z absorber, where they loose energy by ionization and the longitudinal component of momentum is then replenished by RF cavities [11].

The initial goal of the MICE experiment [12] to study a fully engineered cooling cell of the proposed US Study 2 [4], has been downsized in 2014 to a demonstration of ionization cooling with a simplified lattice based on the available RF cavities and absorber-focus coils (see the top panel of figure 2). A dedicated muon beam from ISIS (140-240 MeV/c momentum, tunable between $3 - 10\pi \cdot \text{mm rad}$ input emittance) enters the MICE cooling section after a Pb diffuser of adjustable thickness. The MICE beamline has been characterized by the use of the TOF detectors (with ~ 50 ps resolution), with data taken mainly in summer 2010 [17]. As conventional emittance measurement techniques reach barely a 10% precision, the final measure of emittance will be done in MICE on a particle-by-particle basis by measuring $x, y, x' = p_x/p_z, y' = p_y/p_z, E, t$ with the trackers and the TOF system. Foreseen performances of the MICE cooling cell are shown in the bottom panel of figure 2.

2.1.1 6D cooling

Both a reduction in transverse emittance and longitudinal emittance are needed for a $\mu^+\mu^-$ Higgs factory or a multi-TeV collider, as shown in the left panel of figure 3 from reference [15]. As a direct longitudinal cooling is not feasible, due to the energy-loss straggling that increases the energy spread, the only practical solution is to transfer a fraction of the cooling effect from transverse to longitudinal phase space (via “emittance exchange”), as shown schematically in figure 3. Dispersion is used to create an appropriate correlation between momentum and transverse position/path length. Clearly this is at the expense of a reduced transverse cooling. Some aspects of the “emittance exchange” will be addressed also in the MICE experiment, by inserting LiH wedge absorbers.

One may envisage multi-pass cooling rings [18] and then extract the cooled

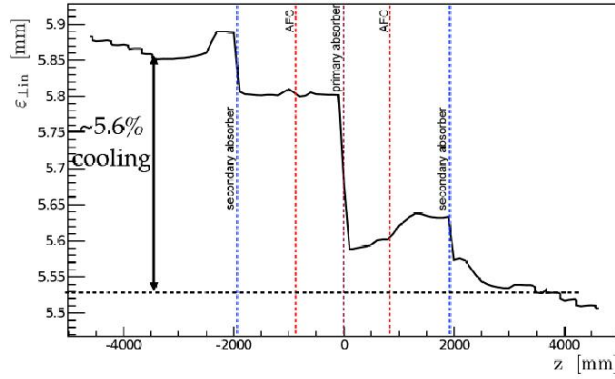
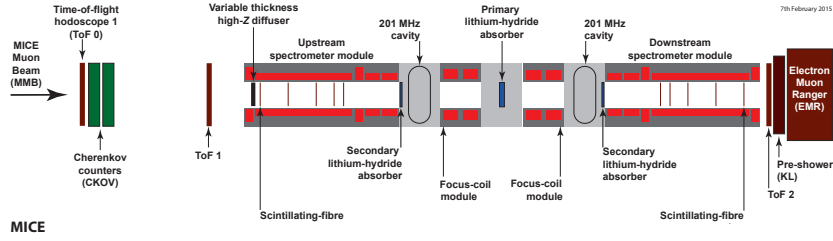


Figure 2: Top panel: view of the MICE experiment at RAL (for more details see [16]). The cooling channel is put between two magnetic spectrometers [13] and two TOF stations [14] to measure particle parameters. Bottom panel: evolution of the 4D emittance in the MICE ionization-colling demo lattice, for a $6\pi \cdot \text{mm}$, 200 MeV/c muon beam.

beams, with a substantial cost reduction, instead of single-pass linear cooling channels, as in MICE. These designs are based on solenoidal focussing strictly interleaved with RF accelerating cavities [19], [20], [21]. Difficult beam dynamics must be handled and performance limits or cost-effectiveness are not completely defined. In a multi-turn cooling ring, the main problems will be connected to beam injection and extraction.

3 Conclusions

The recent discovery of the Standard Model Higgs at about 126 GeV has revived the interest for a compact muon collider: the Higgs-factory. As cooling factors up to 10^6 are needed for a MC, the optimization of the cooling channel is essential. A vigorous *R&D* program is thus needed.

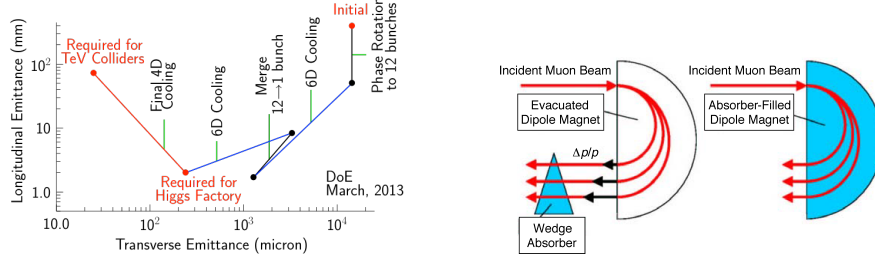


Figure 3: Left panel: emittance evolution path for a $\mu^+\mu^-$ Higgs factory and a multi-TeV collider. Right panel: approaches to emittance exchange, to get 6D cooling [courtesy of Muons Inc.].

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